

Galactic winds and the photo-chemical evolution of elliptical galaxies: the classic model revisited

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1 February 2008

ABSTRACT

We consider the simultaneous chemical, photometric, and gaseous thermal energy evolution of elliptical galaxies. The evolution of chemical abundances in the intracluster medium (ICM) is set by the differing timescales for gas ejection, via supernovae (SNe)-driven winds, from dwarf, normal, and giant ellipticals, and is monitored concurrently. Emphasis is placed upon the influence of, and sensitivity to, the underlying stellar initial mass function (IMF), star formation efficiency, supernovae Type Ia rates, supernovae remnant (SNR) dynamics, and the most recent advances in stellar nucleosynthesis. Unlike many previous studies, we adhere to a wide range of optical (e.g. colour-metallicity-luminosity relationship) and x-ray (e.g. recent ASCA ICM abundance measurements) observational constraints. IMFs biased toward high mass stars, at least during the early phases of star formation, are implicated in order to satisfy all the observational constraints.

Key words: galaxies: abundances - galaxies: elliptical - galaxies: evolution - galaxies: intergalactic medium

1 INTRODUCTION

A rich history exists in the field of elliptical galaxy spectro-chemical evolution. It was recognised early on (e.g. Larson 1974a) that if star formation was to proceed to completion in all ellipticals, then the observed trend of average metallicity with the depth of the galactic potential well (i.e. mass-metallicity relationship) (Baum 1959) would be difficult to establish. The key to understanding this observed correlation was provided by Mathews & Baker (1971) but not fully appreciated until Larson (1974b).

Mathews & Baker (1971) postulated that much of the gas in the interstellar medium (ISM) of ellipticals had been strongly heated by supernovae (SNe) and driven out by a hot galactic wind once the gas thermal energy exceeded that of its gravitational binding energy (at some time t_{GW}), thereby bringing to a halt the bulk of active star formation. Larson (1974b) noted that the binding energy per unit mass of gas is higher in the more massive galaxies, and thus these systems would retain their gas for a longer period of time before reaching t_{GW} , and thus attain a higher metallicity, consistent with the observed mass-metallicity relationship. The subsequent evolution would then be regulated only by gas lost from dying stars. An excellent recent review of galactic winds, from an observational slant, is given by Bland-Hawthorn (1995).

What began with Larson (1974b) has led to a profusion of follow-up SNe-driven galactic wind models (e.g. Ikeuchi 1977; Saito 1979b; Dekel & Silk 1986; Arimoto & Yoshii 1987 (AY87); Matteucci & Tornambè 1987 (MT87); Angeletti & Giannone 1990 (AG90); Ciotti et al. 1991; David et al. 1991; Babul & Rees 1992; Arnaud et al. 1992; Ferrini & Poggianti 1993; Renzini et al. 1993; Okazaki et al. 1993; Bressan et al. 1994; Mihara & Takahara 1994; Elbaz et al. 1995; Nath & Chiba 1995; Gibson & Matteucci 1997). Modern advances in stellar nucleosynthesis, supernova remnant (SNR) shock dynamics and thermal evolution, the role of dark matter, and even basic observational constraints (both in the stellar component of ellipticals and the intracluster medium (ICM) of galaxy clusters) makes a re-examination of the classic wind model a timely one. We have developed a software package, entitled **MEGAW** \equiv **M**etallicity **E**volution with **G**alactic **W**inds, to enable us to study the chemical evolution of ellipticals within the framework of Larson (1974b) classic galactic wind model.

Concurrent to the development of sophisticated wind models was the flourishing field of spectral and photometric evolution of galaxies, the early history being traced in Tinsley's (1980) seminal paper. One need only look to the recent models of Bruzual & Charlot (1993), Bressan et al. (1994), Worthey (1994) and Emsel et al. (1995), for a few state of the art examples. The consideration of chemical evolution

together with photometric evolution is imperative as stellar evolutionary tracks and spectrophotometric calibrations are sensitive to the chemical composition, and elliptical galaxies are complex systems with a distribution of stellar populations. Models which utilise only solar abundance tracks and solar abundance spectra/colours (e.g. Guiderdoni & Rocca-Volmerange 1987; Bruzual & Charlot 1993) fail to explain the observed correlation between the integrated colours and absolute magnitude of ellipticals (e.g. Faber 1977; Bressan et al. 1994) (as well as, obviously, the metallicity-luminosity relationship).

Before embarking upon the construction of a photo-chemical evolution code suitable for both the elliptical galaxies in question and ICM abundances, it is important to be aware of some of the primary observational constraints^{*}:

- *Elliptical CML Relations:* First and foremost, for the underlying ellipticals, the models must honour the observed, present-day colour-metallicity-luminosity (CML) relationships (e.g. Faber 1977). i.e. ellipticals, in general, show increasing metallicity and redder colours, with increasing luminosity.
- *Magnesium Overabundance in Stellar Populations:* [Mg/Fe] in giant ellipticals is $\sim +0.2 \rightarrow +0.3$, with a slight trend toward increasing values with increasing luminosity, albeit with a fairly large degree of scatter (Worthey et al. 1992).
- *Oxygen Overabundance of the ICM:* X-ray observations of the hot ICM of four clusters of galaxies shows an oxygen overabundance relative to iron of [O/Fe]=+0.4 \pm 0.3 (Mushotzky 1994).
- *ICM Iron-Luminosity Relation:* The ICM iron mass (in M_\odot) increases as a function of a cluster's optical luminosity tied up in E+S0s (in $L_{V\odot}$), such that $M_{\text{Fe}}^{\text{ICM}} \approx 0.02 L_V^{\text{E+S0}}$ (Arnaud et al. 1992).
- *Type Ia Supernovae Rates in Ellipticals:* The present-day Type Ia SN rate in giant ellipticals is $R_{\text{Ia}} \approx 0.03 \rightarrow 0.08 \text{ SNU}^\dagger$ (Turatto et al. 1994).

The work described herein is the only study to date to draw upon *all* of the above; the previously mentioned models neglect, or fail to satisfy, one or more of these constraints. Photometric self-consistency is the usual constraint which suffers, primarily due to a past dearth of non-solar calibrations/tracks (although, see Arimoto & Yoshii 1987 and Bressan et al. 1994). Overcoming this major hurdle is only now becoming feasible; specifically, the past two years has seen the release of the first wave of fully self-consistent isochrones, ranging from ultra-low to super metal-rich, isochrones. These isochrone compilations (Worthey 1994 and Bertelli et al. 1994) draw heavily upon Kurucz's (1993) extensive grid of model stellar atmospheres.

Section 2 introduces the galactic wind framework in which **MEGAW** operates. This includes an outline of the relevant chemical evolution equations, as well as a description of the different parametrisations adopted for each of the input ingredients. In Section 3.1 we present a template model against which future comparisons will be made. Sections 3.2.1 to 3.2.6 then systematically explore the sensitiv-

ity of the model predictions to the different input ingredients. Such an analysis is long overdue, as previous studies tended to simply select one preferred combination of parameters without illustrating the ramifications of said selection. A summary of the primary conclusions can be found in Section 4.

2 THE CLASSIC GALACTIC WIND MODEL

2.1 Supernova progenitors and rates

We adopt the “single degenerate” model of Whelan & Iben 1973 for Type Ia SNe in which the progenitors are C/O-white dwarfs in close binary systems accreting material from a secondary companion. Type II SNe are presumed to originate via the core bounce-induced explosion of single massive star (i.e. $m \gtrsim 8 M_\odot$) progenitors. Arnett (1996) provides an excellent review of the relevant SN physics.

As in Matteucci & Tornambè (1987), we have chosen to use the SN rate formalisms proposed by Greggio & Renzini (1983). Calling m_1 and m_2 the mass of the primary and secondary, respectively (i.e. $m_B = m_1 + m_2$), and denoting the secondary mass fraction $\mu \equiv m_2/m_B$, we can write the Type Ia SN rate $R_{\text{Ia}}(t)$ as:

$$R_{\text{Ia}}(t) = A \int_{m^1}^{m_{\text{BM}}} \frac{\phi(m)}{m} \left\{ \int_{\mu_{\text{m}}}^{0.5} f(\mu) \psi(t - \tau_{m_2}) d\mu \right\} dm \quad (1)$$

where $m^1 = \max[2m_t, 3.0]$. For a given t , m_t represents the mass of stars currently leaving the main sequence. $\phi(m)$ is the IMF, by mass. The distribution function for the mass fraction of secondaries is taken to be proportional to μ^2 , and the minimum mass fraction μ_{m} contributing to the SN Type Ia rate at time t is $\mu_{\text{m}} \equiv \max[m_2(t)/m_B, 1 - 0.5m_{\text{BM}}/m_B]$ (Greggio & Renzini 1983). A represents the mass fraction of the IMF which is tied up in binary systems with total masses in the range $m_{\text{Bm}}(3.0 M_\odot) \rightarrow m_{\text{BM}}(16.0 M_\odot)$. A is fixed *a posteriori* by ensuring reproduction of the current rate of Type Ia events in ellipticals.

The Type II SN rate $R_{\text{II}}(t)$ is composed of two terms – one for all stars with initial masses greater than $16.0 M_\odot$, and one for the fraction (i.e. $1 - A$) of stars in the mass range $8.0 \rightarrow 16.0 M_\odot$ which are not part of binary systems:

$$R_{\text{II}}(t) = (1 - A) \int_{\max[m_t, 8.0]}^{m_{\text{BM}}} \frac{\phi(m)}{m} \psi(t - \tau_m) dm + \int_{m_{\text{BM}}}^{m_{\text{U}}} \frac{\phi(m)}{m} \psi(t - \tau_m) dm. \quad (2)$$

Single low and intermediate mass stars ($m \lesssim 8.0 M_\odot$) are presumed to end their lives as white dwarfs, after passing through a thermally pulsing-asymptotic giant branch (TP-AGB) and planetary nebulae (PNe) ejection phase (Renzini & Voli 1981).

2.2 Stellar lifetimes

Stars return gas and metals to the ISM via stellar winds, SNe events and envelope ejection, depending upon the initial mass and metallicity. The bulk of the ejection occurs near the end of the star's lifetime $\tau(m, Z)$, with stellar evolutionary theory providing the functional form of τ .

^{*} $H_0 \equiv 50 \text{ km/s/Mpc}$ assumed throughout.

[†] $1 \text{ SNU} \equiv 1 \text{ SN/century}/10^{10} L_{\text{B}\odot}$.

Figure 1 illustrates three popular compilations of τ versus initial mass m : AY87 and AG90 adopted the singular power-law form from Talbot & Arnett (1971), which predicts excessively long lifetimes for stars in the $\sim 1 \rightarrow \sim 50 M_\odot$ range; MT87 used Güsten & Mezger’s (1982) parametrization of the Alcock & Paczynski (1978) and Becker (1981) stellar models[‡]. The best approach available today is to adopt the metallicity-dependent lifetimes provided by newer, more extensive, grids of stellar evolution tracks (e.g. the Padova Group – Fagotto et al. 1994 or the Geneva Group – Schaller et al. 1992). Unless otherwise noted, we use the lifetimes from Schaller et al.’s (1992) $Z=0.02$ grid, although for lower metallicity systems, their $Z=0.001$ predictions are adopted.

Varying the selection of stellar lifetime formalism is considered in Section 3.2.1.

Figure 1. Stellar lifetimes τ as a function of initial mass m . TA71=Talbot & Arnett (1971); GM82=Güsten & Mezger (1992); SSMM92=Schaller et al. (1992).

2.3 Chemical evolution

Models for chemical evolution follow abundance changes in the ISM of a region, and the resulting abundance distributions in stars. A detailed derivation of the fundamental equations can be found in Talbot & Arnett (1971) and Tinsley (1980). We have chosen to couple these equations (appropriate for the one-zone model with instantaneous mixing of

gas and relaxation of the instantaneous recycling approximation) with the classic galactic wind model formalism of Matteucci & Tornambè (1987).

The mass of the ISM (i.e. gas mass $M_g(t)$) changes through star formation and ejection:

$$\frac{dM_g(t)}{dt} = -\psi(t) + E(t), \quad (3)$$

where $\psi(t)$ is the mass of gas being converted into stars per unit time:

$$\psi(t) = \nu M_g(t), \quad (4)$$

and $E(t)$ is the total ejection rate of gas from all stars:

$$\begin{aligned} E(t) = & \int_{m^1}^{m_{\text{BM}}} \phi(m) \psi(t - \tau_m) R(m) dm + \\ & A \int_{m^2}^{m_{\text{BM}}} \phi(m) \left\{ \int_{\mu_m}^{0.5} f(\mu) \psi(t - \tau_{m_2}) R(m_2) d\mu \right\} dm + \\ & (1 - A) \int_{m^2}^{m_{\text{BM}}} \phi(m) \psi(t - \tau_m) R(m) dm + \\ & \int_{m^3}^{m_U} \phi(m) \psi(t - \tau_m) R(m) dm. \end{aligned} \quad (5)$$

The star formation rate denoted by equation 4 is equivalent to assuming a Schmidt (1959) Law with exponent one. The respective integration lower limits to equation 5 are $m^1 = \max[m_t, m_L]$, $m^2 = \max[m_t, m_{\text{BM}}]$, and $m^3 = \max[m_t, m_{\text{BM}}]$. $R(m) = [1 - w_m/m]$ represents the fractional mass of a star of initial mass m and remnant mass w_m , ejected back into the ISM after its stellar lifetime τ . The lifetime τ and remnant mass w_m both depend upon a star’s metallicity Z . Unless otherwise noted, we use the remnant mass formalism of Prantzos et al. (1993). Following the majority of the earlier studies, we take the star formation rate ψ during the post-galactic wind phase to be zero[§].

The first integral on the right-hand side of equation 5 represents the rate at which gas is being returned to the ISM at time t from single low mass ($m \lesssim 8 M_\odot$) stars ending their lives as white dwarfs. Integral two is the gas mass return rate from stars in binary systems which end their lives as Type Ia SNe. Integral three is the rate of gas mass ejection at time t from single stars in the mass range $3.0 \rightarrow 16.0 M_\odot$. For $m < 8.0 M_\odot$, these single stars end as white dwarfs, whereas for $8.0 < m < 16.0 M_\odot$ they end as Type II SNe. The final integral is the gas ejection rate from single massive stars (i.e. $16.0 M_\odot \rightarrow m_U$) which end their lives as Type II SNe.

The equation governing the evolution of the mass of metals $M_Z(t) \equiv M_g(t)Z(t)$ in the ISM gas is

[§] For the broad-band colours to which the current code is aimed at reproducing (e.g. B-V, V-K, etc), relaxing such a restriction does not dramatically alter the model results; Arimoto (1989), Ferrini & Poggianti (1993), and Elbaz et al. (1995), each provide evidence for the limited importance of post- t_{GW} star formation. On the other hand, such an assumption is most likely *not* an ideal one when one is more concerned with replicating specific line indices (e.g. Worthey et al. 1995); because we are still in the process of extending MEGaW’s functionality to include full spectral synthesis, we have chosen the more conservative $\psi(t > t_{\text{GW}}) \equiv 0$ route, for the time being.

[‡] Because Alcock & Paczynski (1978) and Becker (1981) did not extend their stellar evolution studies below $m = 2 M_\odot$, nor consider metallicities besides $Z=0.03$, Güsten & Mezger (1982) were forced to extrapolate into regimes the models were not designed to replicate. This results in considerably shorter lifetimes for solar and sub-solar mass stars, in comparison with present-day models.

$$\frac{dM_Z(t)}{dt} = -Z(t)\psi(t) + E_Z(t), \quad (6)$$

where $E_Z(t)$ is the total ejection rate of new and old metals (i.e. processed and unprocessed, respectively). The appropriate form for $E_Z(t)$ can be recovered by replacing $mR(m)$ in equation 5 with $m_{Z,m}^{\text{ej}}$ (Section 2.4), the total mass of metals ejected from a star of initial mass m and initial metallicity $Z(t - \tau_m)$.

As a final sanity check on our numerical solutions of equations 3 and 6, we were fortunate to find several experts in the field willing to run well-defined standard models with which to compare with our own code – specifically, Francesca Matteucci (SISSA/Trieste - Matteucci 1992), Frank Timmes (Chicago - Timmes et al. 1995) and Leticia Carigi (CIDA - Carigi 1994). Disregarding minor differences incurred by the various approaches to nucleosynthesis in the highly uncertain $m \sim 8 \rightarrow 11 M_\odot$ range, and assumptions regarding the fate of unprocessed metals in low mass star ejecta, the results of the intercomparison were more than satisfactory, and put this author’s mind at ease. The biggest single discrepancy occurred in the magnesium evolution, with Matteucci’s code predicting lower values, a result which was anticipated, and simply reflects a difference in the adopted Mg yield between the two codes, and not a numerical problem. We return to this difference in subsequent sections.

2.4 Stellar nucleosynthesis yields

The key ingredient in any chemical evolution code will obviously be the adopted nucleosynthetic stellar yields (i.e. the mass of element i ejected by a star of initial mass m during the course of its lifetime). These yields, as provided by practitioners of stellar evolution and nucleosynthesis, are in general parametrised in terms of a progenitor’s initial mass m , metallicity Z , and “environment” (i.e. single or binary system).

Type II SNe are responsible for producing the bulk of heavy elements; near the end of the progenitor’s (Section 2.1) lifetime, during the carbon-burning phase, a He-exhausted core (primarily iron-peak nuclei) becomes effectively isolated from the rest of the star. The subsequent core collapse leads to $\sim 10^{51}$ erg being deposited into the overlying mantle (neutrino energy), the final result being a compact remnant (neutron star or black hole) and an ejected envelope, enriched in metals.

The last few years have seen an explosion of interest in massive star (i.e. $m \gtrsim 10 M_\odot$) evolution, the result being the newly (or soon-to-be) available metallicity-dependent yields of Maeder (1992, hereafter M92), Woosley & Weaver (1995, hereafter WW95), and Langer & Henkel (1995, hereafter LH95). Improved solar metallicity tabulations from Arnett (1991, hereafter A91) and Thielemann et al. (1995, hereafter TNH95) have also come on-line. Each of these five options are available in **MEGAW**.

Each of the compilations start at the approximate lower mass cut-off for Type II SNe (i.e. $\sim 10 \rightarrow 12 M_\odot$), but have very different upper mass limits. M92 goes as high as $120 M_\odot$ for both $Z=0.001$ and $Z=0.020$; A91 goes to $85 M_\odot$, but only for $Z=0.020$; LH95 have an upper limit of $50 M_\odot$ for their models, with $Z=0.002$ and $Z=0.020$; WW95 have the best metallicity coverage ($Z=0.0000, 0.00002, 0.0002,$

0.0020 , and 0.0200), with an upper limit of $40 M_\odot$; TNH95 only go as high as $25 M_\odot$, and only for $Z=0.02$. We mention in passing that WW95 consider three different models for $m \geq 30 M_\odot$, their so-called A, B, and C models. These differ in the amount of energy imparted by the piston in their models at explosion initiation. Following Timmes et al. (1995), we use the “B” models in this mass regime.

While each source provides the yields for H, He, Z, C, and O, the remaining elements under consideration here are covered by some, but not by others. N is listed by all except A91, while Mg, Si, and Fe were not part of the M92 or LH95 tables. For the sake of self-consistency with the stellar evolution models, we do not attempt to “mix-and-match” in order to “fill-in” those elements missing in one compilation with those found in another, as the input physics between models is usually incompatible from one to another. The mix-and-match approach is a necessary one for those using the M92 yields, as is seen in Carigi (1994) and Giovagnoli & Tosi (1995) – e.g. for the evolution of Fe, the former adopts a yield of $0.075 M_\odot$ for all Type II SNe, irrespective of progenitor mass or metallicity, while the latter adopts the Fe yields of Arnett (1978).

A detailed comparison of the five Type II SNe yield options will be published elsewhere (Gibson 1997, in preparation). This will include a comprehensive outline of the different assumptions regarding the input physics. We refer the reader to each of the relevant references for tabulated values of $m_{i,m}^{\text{ej}}$ (equation 6), although we do draw attention here to several interesting points which can be made from a cursory glance at some of the predicted yield ratios from said compilations.

- **[O/Fe]:** Mushotzky (1994) has demonstrated that the intracluster media (ICMs) of the four clusters in their ASCA analysis, is overabundant in oxygen when compared to iron, by factors of $\sim 2 \rightarrow 5$, with respect to the solar ratio. This observation is reflected by the shaded region of Figure 2. Contrast this constraint with the predicted [O/Fe] yield ratios from the three compilations which include iron (i.e. WW95, TNH95, A91) – it is readily apparent that galactic ejecta enriched in the byproducts of Type II SNe of mass $m \gtrsim 20 M_\odot$ are the *necessary* primary[¶] contributor of the bulk of these heavy elements in the ICM. The yield ratios adopted in Matteucci’s (1992) chemical evolution code are indicated by the dotted line in Figure 2.^{||} For $m \gtrsim 30 M_\odot$, A91’s different mass cut results in more iron being ejected for a given initial mass (Gibson 1997, in preparation). TNH95’s significantly coarser grid makes a de-

[¶] Because the other primary source of heavy element enrichment – i.e. Type Ia SNe – have $[O/Fe] \approx -1.53$ (Thielemann et al. 1993), they can only act to drive [O/Fe] downward from the observed overabundance. As Type Ia SNe tend to dominate the enrichment history beyond $t \gtrsim 1$ Gyr (Matteucci & Greggio 1986; Section 3.1), this ICM observation provides indirect evidence that early, Type II SNe-driven winds are the dominant mechanism at play.

^{||} Matteucci (1992) assumed a constant oxygen yield of $\sim 0.48 M_\odot$ for all stars of initial mass $9 \lesssim m \lesssim 15 M_\odot$, suppressing the ejection of all other heavy elements. On the other hand, following Iwamoto et al. (1994), we have chosen to suppress the ejection of *all* newly synthesised metals in the $8 \rightarrow 11 M_\odot$ range.

tailed comparison difficult, and simple extrapolation to higher masses was assumed.

- *[Mg/Fe]*: The stellar populations of elliptical galaxies possess a $\sim 50 \rightarrow 100\%$ overabundance of magnesium-to-iron, in comparison with the solar ratio (see the shaded region of Figure 3 – Worthey et al. 1992). Considering the oxygen overabundance relative to iron seen in cluster ICMs, with the fact that the bulk of star formation in the contributing ellipticals ceases subsequent to the galactic wind epoch, this should not be entirely unexpected.** Significant differences in the behaviour of *[Mg/Fe]* appear to exist in the stellar models in question. Factors of three to ten between A91, WW95, and TNH95, at a given mass, are apparent. The WW95 curve lies consistently below A91 and TNH95 for $m < 35 M_{\odot}$. These obvious differences must be borne in mind when attempting to replicate Worthey et al. 's (1992) observation of $[Mg/Fe] \approx +0.2 \rightarrow +0.3$ in ellipticals. The dotted line in Figure 3 shows the adopted *[Mg/Fe]* in Matteucci's (1992) code.††

The yields for single low and intermediate mass stars (i.e. $m \leq 8 M_{\odot}$) are taken from Renzini & Voli (1981, hereafter RV81). Stars in this mass range are seen to be important contributors to He, C, and N. These lower mass stars are not capable of igniting C in their cores (their masses are too low), and end their lives as He or C/O white dwarfs, after passing through several dredge-up phases, a thermally pulsing phase on the upper AGB, and finally a PN ejection. We generally use RV81's preferred models with the Reimers' (1975) mass loss parameter on the red giant branch (RGB) $\eta = 0.33$, and the ratio of the mixing length to the pressure scale height $\alpha = 1.5$.‡‡

Stars with initial masses between ~ 8 and $\sim 11 M_{\odot}$ undergo non-degenerate C-burning and develop O+Ne+Mg cores. Whether these highly enriched cores contribute their newly synthesised metals to the ISM via thermonuclear explosion, or else undergo core collapse, trapping the yields

** Type Ia SNe contribute Mg and Fe in the ratio $[Mg/Fe] \approx -1.63$ (Thielemann et al. 1993). Similar to the ICM $[O/Fe]$, this lends support to the notion that a Type II SNe-driven wind, as opposed to a later Type Ia-driven one, is dominating the evolution.

†† Matteucci's *[Mg/Fe]* (Figure 3) is fairly flat, and, more importantly, negative for all $m \lesssim 35 M_{\odot}$. This would appear to be due to a lower adopted magnesium yield in her code, which was based upon the state-of-the-art during the mid-1980s. Recalling that the *[Mg/Fe]* of the stellar component of giant ellipticals is typically $+0.2 \rightarrow +0.3$, one can anticipate that fairly extreme IMFs, with a substantial $m \gtrsim 35 M_{\odot}$ component, would be *necessary* with her code, in order to recover such super-solar Mg overabundances. This is indeed what Matteucci (1994) found.

‡‡ Specifically, Tables 3d and 3i ($Z=0.020$ and 0.004 , respectively) from RV81 for $m \geq 4 M_{\odot}$, and Tables 3a and 3h ($Z=0.020$ and 0.004 , respectively) for $m < 4 M_{\odot}$, were adopted. The RV81 models are admittedly outdated, and our code has subsequently been updated to accommodate RV81, as well as the newer Marigo et al. (1996) and van den Hoek & Groenewegen (1997) compilations. None of the results presented herein depend upon the selection of low mass stellar yields, and we have simply retained RV81 for the discussion which follows. A companion paper (Gibson & Mould 1997) contrasts these compilations, as pertaining to chemical evolution of the Galactic halo.

Figure 2. Comparison of the Type II SNe ejecta $[O/Fe]$ from three of the sources discussed in Section 2.4. The shaded region represents the observed ICM $[O/Fe]$ (Mushotzky 1994). Also shown is the yield ratio adopted in Matteucci's (1992) chemical evolution code.

in the remnant neutron star, is still unclear (e.g. Matteucci 1991). Much depends upon the assumed electron capture onto ^{24}Mg and ^{20}Ne , but the controversy does seem to be converging toward the picture in which core collapse is favoured, and the elemental enrichment is basically restricted to that deposited during the pre-SN stellar wind (Iwamoto et al. 1994), and this is what has been assumed in **MEGAW**. For comparison, Matteucci (1992) suppresses all newly synthesised metals except oxygen, and Timmes et al. (1995) simply interpolate linearly between the highest mass in RV81 (i.e. $8 M_{\odot}$) and the lowest mass in WW95 (i.e. $\sim 11 M_{\odot}$).

The yields for each Type Ia event are taken from the improved $Z=0.02$ W7 Model presented in Thielemann et al. (1993). Of the $\sim 1.36 M_{\odot}$ of metals ejected per event, iron is by far the largest contributor ($\sim 0.74 M_{\odot}$), with lesser amounts being ejected in the form of Si, O, C, and Mg (i.e. $0.15, 0.14, 0.05$, and $0.01 M_{\odot}$, respectively). These yields are assumed to be metallicity-independent – a reasonable assumption based upon the similarity of Thielemann et al. 's (1993) $Z=0.02$ and $Z=0.00$ models.

Unless otherwise noted, the default yields adopted throughout this paper are culled from WW95 ($m \gtrsim 10 M_{\odot}$), RV81 ($m \lesssim 8 M_{\odot}$), and Thielemann et al. (1993) (for Type Ia SNe). How the predicted chemical evolution is affected by a choice of yield tables different from that of WW95 is discussed further in Section 3.2.2, and in particular, by Gibson (1997, in preparation).

2.5 Thermal and binding energy evolution of the ISM

Figure 3. Comparison of the Type II SNe ejecta [Mg/Fe] from three of the sources discussed in Section 2.4. The shaded region represents the observed elliptical galaxy [Mg/Fe] (Worthey et al. 1992). Also shown is the yield ratio adopted in Matteucci’s (1992) chemical evolution code.

2.5.1 ISM thermal energy

For gas to be expelled from a galaxy, the thermal energy of the gas heated by SN explosions and stellar mass loss must overcome the binding energy of the gas (Larson 1974b) – i.e. the galactic wind will start at a certain time t_{GW} when

$$\begin{aligned} E_{\text{th}}(t_{\text{GW}}) &\equiv E_{\text{thIa}}(t_{\text{GW}}) + E_{\text{thII}}(t_{\text{GW}}) + E_{\text{thW}}(t_{\text{GW}}) \\ &= \Omega_{\text{g}}(t_{\text{GW}}), \end{aligned} \quad (7)$$

where $E_{\text{th}}(t)$ is the total thermal energy in the gas at the time t , given by the sum of the contribution from SNe Types Ia and II ($E_{\text{thIa}}(t)$ and $E_{\text{thII}}(t)$, respectively) and thermalised kinetic energy from mass loss in high mass ($m \gtrsim 12 M_{\odot}$) stars ($E_{\text{thW}}(t)$, which is given by equation 5 of Gibson 1994a).

The SNe thermal energy components of equation 7 can be written (Saito 1979b):

$$\begin{aligned} E_{\text{thIa}}(t) &= \int_0^t \varepsilon_{\text{thSN}}(t - t') R_{\text{Ia}}(t') dt' \\ E_{\text{thII}}(t) &= \int_0^t \varepsilon_{\text{thSN}}(t - t') R_{\text{II}}(t') dt', \end{aligned} \quad (8)$$

where t' is the SN explosion time, R_{Ia} and R_{II} are the SNe Ia and II rates (equations 1 and 2, respectively), and $\varepsilon_{\text{thSN}}$ is the equation governing the evolution of the thermal energy content in the interior of a supernova remnant (SNR) (Section 2.6). In the post-wind phase ($t > t_{\text{GW}}$), the lower limit on the time integrals in equations 7 is taken to be t_{GW} .

2.5.2 ISM binding energy

In order to determine the onset of the galactic wind, we need to compute the binding energy of the gas as a function of time, $\Omega_{\text{g}}(t)$. As discussed in Matteucci (1992), $\Omega_{\text{g}}(t)$ is influenced by the presence of dark matter, and its distribution relative to the luminous (i.e. gas + stars) component. We consider two different scenarios: (i) one in which the two components trace each other, following the prescription of Saito (1979b), and (ii) one in which the luminous component is embedded in a massive, diffuse halo of dark matter, adopting the two-component, self-consistent models of Bertin et al. (1992).

Dark matter traces luminous component

Following Arimoto & Yoshii (1987), Matteucci & Tornambè (1987), and Angeletti & Giannone (1990), we first represent elliptical galaxies as spheroidal, homogeneous systems, with a characteristic gravitational radius R_{G} , and total mass $M_{\text{G}} \equiv M_{\text{L}} + M_{\text{D}}$ (i.e. the sum of the luminous and dark components). Assuming the virial theorem holds, the total binding energy of the system Ω_{G} can be written as

$$\Omega_{\text{G}} = \frac{GM_{\text{G}}^2}{2R_{\text{G}}}. \quad (9)$$

Following Saito (1979b), the binding energy of the gaseous component $\Omega_{\text{g}}(t)$ alone can be written

$$\Omega_{\text{g}}(t) = \Omega_{\text{G}} \frac{M_{\text{g}}(t)}{M_{\text{G}}} \left(2 - \frac{M_{\text{g}}(t)}{M_{\text{G}}} \right), \quad (10)$$

It is this binding energy which is compared with the gaseous thermal energy calculated from equation 7 in order to determine the time of galactic wind onset t_{GW} .

Diffuse dark halos

While the previous section’s analysis is suitable for models in which the dark matter component is distributed similarly to the luminous component, it is not suitable for the more generally accepted scenario in which the gas and stars are embedded in a massive diffuse halo of dark matter (e.g. Bertin et al. 1994, and references therein). To model such distributions, we follow the prescription laid out in Bertin et al. (1992). In this context, the binding energy of gas is expressed as

$$\Omega_{\text{g}}(t) = \Omega_{\text{L}}(t) + \Omega_{\text{LD}}(t), \quad (11)$$

where the gravitational energy of the gas due to the luminous matter Ω_{L} (dropping the implicit time dependency) is

$$\Omega_{\text{L}} = \frac{GM_{\text{g}}M_{\text{L}}}{2R_{\text{L}}} \quad (12)$$

and the gravitational energy of the gas due to the dark matter Ω_{LD} is

$$\Omega_{\text{LD}} = \frac{GM_{\text{g}}M_{\text{D}}}{R_{\text{L}}} \Omega'_{\text{LD}}. \quad (13)$$

The interaction integral Ω'_{LD} is estimated to be

$$\Omega'_{\text{LD}} \approx \frac{1}{2\pi} \frac{R_{\text{L}}}{R_{\text{D}}} \left[1 + 1.37 \left(\frac{R_{\text{L}}}{R_{\text{D}}} \right) \right]. \quad (14)$$

R_{D} and M_{D} is the radial extent and mass of the dark matter halo. $M_{\text{D}} \gtrsim (2 \rightarrow 10)M_{\text{L}}$ and $R_{\text{D}} \gtrsim 5R_{\text{L}}$ are favoured in

these two-component models when applied to large samples of ellipticals (Saglia et al. 1992).

Mass-energy-radius relations

One last piece of the puzzle necessary to solve for the gaseous binding energy is obvious upon re-inspection of equations 9, 10 and 11 – a relationship between the galaxy mass, radius, and binding energy. To this end, we use empirical relationships derived by Saito (1979a) from fitting Michie-King models to the surface brightness distribution and line-of-sight velocity dispersions for a wide range of nearby spheroids (ranging from globular clusters to giant ellipticals). This first gives the Ω_L – M_L relation:

$$\Omega_L = 1.64 \times 10^{60} \left[\frac{M_L}{10^{12}} \right]^{1.45}, \quad [\text{erg}] \quad (15)$$

where M_L is in solar masses. Combining equations 9 and 15, we can write the virial radius of our spheroidal galaxies in terms of the mass as

$$R_L = 26.0 \left[\frac{M_L}{10^{12}} \right]^{0.55}. \quad [\text{kpc}] \quad (16)$$

Both these relations were derived assuming a Hubble constant $H_0 = 75 \text{ km/s/Mpc}$. Note that one should replace the subscript “L” with “G”, in equations 15 and 16, when adopting the scenario in which the luminous and dark components are distributed similarly.

We should stress the uncertainty in using these empirical Ω_L – M_L – R_L relations which are based upon present-day properties of spheroidals. Observational constraints of this ilk, for primeval galaxies, simply do not exist. For example, if the proto-galaxy has not fully collapsed at the epoch of galactic winds, then the binding energy at this point might be a factor of ~ 2 less than that predicted by equation 15 (Arimoto & Yoshii 1989); conversely, mass lost at t_{GW} (either impulsively, or gradually over a long timescale) would imply that the binding energy at $\sim t_{\text{GW}}$ might be anywhere from $\sim 1 \rightarrow 4$ times greater than that predicted by equation 15. This latter scenario was explored by Hills (1980), Vader (1987), and Angeletti & Giannone (1991). We recognise that use of Saito’s (1979a) present-day relationships is not ideal, but to be conservative, restrict ourselves to them regardless^{§§}.

2.6 Supernova remnant interior thermal energy evolution

Another of the primary ingredients to any SNe-driven galactic wind model is the assumed evolution of the thermal energy made available to the ISM by each SN event. It is the hot, dilute gas in the interior of these SN remnants (SNRs)

which contains virtually all of this thermal energy (Cox 1972).

For our modeling, we have considered a number of thermal evolutionary scenarios for SNRs, each of which has its basis in either the classic models of Cox (1972) and Chevalier (1974) (the “**A**” models, below), or the more sophisticated treatment of Cioffi et al. (1988) (the “**B**” models, below). The latter models incorporate additional radiative cooling processes and explicit metallicity effects. The relevant equations governing each of the models have already been outlined in Gibson (1994b, 1995). A cursory treatment can also be found in Matteucci (1997). We refer the reader to these papers for the *minutiae*, and for this paper we simply provide the following qualitative listing:

- (i) **Model A₀**: SNR shells continue to expand and cool radiatively *ad infinitum* (after Cox 1972 and Chevalier 1974). The SNR interior thermal energy evolves as $\varepsilon_{\text{thSN}} \propto (t/t_c)^{-0.6}$, where t_c is the shell cooling time. This is the classic scenario adopted by virtually all previous studies.
- (ii) **Model A₁**: Parallels A₀ until the interior pressure in the SNR is reduced to that of the pressure of the ambient ISM, thereafter merging and becoming indistinguishable from the surrounding ISM. No further radiative cooling of the interior is considered.
- (iii) **Model B₀**: Shells continue to expand and cool radiatively *ad infinitum* (after Cioffi et al. 1988). The late-time behaviour of $\varepsilon_{\text{thSN}}$ varies as $\propto (t/t_c)^{-1.0}$. The additional factor of $(t/t_c)^{-0.4}$ in $\varepsilon_{\text{thSN}}$ is due to Cioffi et al.’s (1988) inclusion of radiative cooling, neglected in the classic Cox (1972) and Chevalier (1974) studies. This is the modern analogue to Model A₀.
- (iv) **Model B₁**: Shells halt both their expansion and radiative cooling at the ISM merging time alluded to in Model A₁’s description.
- (v) **Model B₂**: Shells halt their expansion but continue to cool radiatively *ad infinitum* (i.e. $\varepsilon_{\text{thSN}} \propto (t/t_c)^{-0.4}$ at later evolutionary stages).
- (vi) **Model B₃**: Parallels Model B₂ until reaching a cooling time beyond which radiative cooling is no longer efficient.
- (vii) **Model B₃’**: Parallels Model B₃, unless expanding shells start coming into contact, and overlapping with, neighbouring shells, in which case the expansion term is dropped earlier.

The above models can be compared visually by referring to Figure 1 of Gibson (1994b). Unless stated otherwise, we shall use Model B₂ for the late-time evolution of $\varepsilon_{\text{thSN}}(t)$.

3 ANALYSIS

3.1 The “template” models

In order to examine the sensitivity of model predictions to the various input ingredients, we first describe a working template of models which, in general, satisfy the observational constraints outlined in Section 1. The pertinent facts are listed in Table 1. We draw attention to the star formation efficiency ν in column 2; for the chosen set of input ingredients ν , was treated as a free parameter and chosen to ensure

^{§§} If the Ω_L – M_L – R_L relation is really a factor of four greater than that predicted by equation 15, then for a given value of the star efficiency ν , t_{GW} will occur up to an order of magnitude later than normally expected. This has the undesired effect of driving the colours/metallicities too red/high; increasing ν appropriately to compensate drives t_{GW} down to comparable values encountered using the canonical expression. For the analysis which follows, this difference is not important.

that the present-day CML relationships (columns 7 to 10) were recovered, as reflected by the solid curves in Figures 6 and 7. This parallels Arimoto & Yoshii’s (1987) treatment of ν . Following the procedure outlined in Gibson (1996a), the V-band luminosity-weighted metallicity $[< Z >]_V$ (column 10) is computed for each model elliptical.

The photometric evolution was coupled to the chemical evolution as outlined in Gibson (1996a). In general, the metallicity-dependent isochrones of Worthey (1994,1995) were adopted, although when those of Bertelli et al. (1994) were used, the distinction is made.

Our working template was generated using a time- and metallicity-independent form of the Salpeter (1955) IMF, with $m_\ell = 0.2 M_\odot$ and $m_U = 65.0 M_\odot$. The metallicity-dependent yields of WW95 were used for Type II SNe. The thermal evolution of the ISM was governed by Model B₂ (Section 2.6). Following Matteucci (1992), diffuse dark matter halos with mass and radial extent ratios relative to the luminous component of ten were used.

A binary parameter $A = 0.03$ (equation 1) was chosen *a posteriori* to ensure that the Type Ia SN rate (column 11) was consistent with that observed in the local elliptical population (Turatto et al. 1994). The stellar population of the giant ellipticals in our template have $[Mg/Fe]_* \approx +0.15$, which is only marginally lower than the $\sim +0.2 \rightarrow +0.3$ observed (Worthey et al. 1992).

Finally, the mass of gas, oxygen, and iron (columns 4, 5, and 6) ejected in the galactic wind at t_{GW} (column 3) are also provided in Table 1.

Figure 1 of Gibson (1996b) illustrates the evolution of elemental abundance of the primary metals for the $M_g(0) = 10^{12} M_\odot$ model of Table 1.

Figure 4 shows the relevant Type II and Ia SNe rates for this same $10^{12} M_\odot$ template model. As expected, beyond t_{GW} , the Type II rate quickly drops to zero as star formation has ceased (and Type II progenitors have $m \gtrsim 10 M_\odot$), whereas the Type Ia SNe \P continue right up until the present-day (the value shown at $t = 12$ Gyr reflecting the observed value in local ellipticals – Turatto et al. 1994). The first Type Ia SNe do not appear until $t \approx 35$ Myr (lifetime of an $8 M_\odot$ star – the most massive secondary allowed in our SNe Ia formalism – Section 2.1), hence the delay in R_{Ia} , relative to R_{II} , seen in Figure 4.

3.2 Influence of the ingredients

The following six subsections provide at least a cursory examination of the influence of each of the major input ingre-

\P Recall from Section 2.1 that in the binary Type Ia SNe scenario, ratios of secondary-to-primary mass of ~ 1 are favoured, and that the explosion “clock” is set by the lifetime of the secondary. Imposing the chosen $3 M_\odot$ minimum-system-mass means that beyond ~ 3 Gyr (i.e. the lifetime of a $1.5 M_\odot$ star), one becomes restricted to mass ratios less than unity, with the ratio getting smaller and smaller as time goes by, and thus the distribution function $f(\mu)$ of equation 1 favours less probable values. This results in an expected “break” and subsequent “downturn” in the Type Ia SNe rate at precisely the point seen in Figure 4. This downturn is also seen in Figure 1 of Greggio & Renzini (1993).

Figure 4. Time-dependence of the Type Ia and II SNe rates for the $M_g(0) = 10^{12} M_\odot$, SNe energy Model B₂, template. The galactic wind epoch t_{GW} (and hence cessation of star formation) is noted.

dients. As the parameter space can be large, we will restrict the analysis to just a few pertinent examples, from which the importance of the relevant parameter can be addressed. Of particular importance will be the effect upon t_{GW} , as this sets the temporal extent of the star formation phase in these galactic models, and thus influences heavily the predicted present-day photo-chemical properties of the resultant stellar populations. We shall see that the results are sensitive to some of the ingredients, and insensitive to others.

3.2.1 Stellar lifetimes

Using the least and most massive template models of Table 1, we now vary the stellar lifetime formalism in order to view its influence upon the predicted present-day photometric and chemical properties. Four different forms were tried – the two Schaller et al. (1992) forms ($Z=0.001$ and $Z=0.020$: SSMM92₁ and SSMM92₂, respectively); Güsten & Mezger (1982, hereafter GM82); and Talbot & Arnett (1971, hereafter TA71). Each were shown in Figure 1. Re-examination of this figure should lead one to the intuitive conclusion that the results, for all but perhaps the TA71 “single power-law”, should be relatively insensitive to the chosen τ form.

Table 2 shows in a more quantitative sense that this is true. For discussion purposes, and the sake of brevity, let us restrict ourselves to the $M_g(0) = 10^{12} M_\odot$ model. Very little difference is encountered when switching between the GM82 and SSMM92_{1,2} lifetimes – recall from Section 2.2 that the former was based upon older, super-solar metallicity ($Z=0.03$), stellar models, whereas the latter allows for a more modern prescription for stellar evolution theory, and two different metallicities ($Z=0.001$ and $Z=0.020$). The lower metallicity SSMM92₁ form leads to marginally later wind epochs ($\sim 5\%$ later), which in turn leads to marginally

Table 1. Template Models: Nucleosynthetic yield sources are Woosley & Weaver (1995) for high mass stars, Renzini & Voli (1981) for single low and intermediate mass stars, and Thielemann et al. (1993) for binary-progenitor SNe Type Ia. Luminosities and colours derived from Worthey’s (1994,1995) isochrones. SNe remnant thermal energy follows Model B₂ of Section 2.6, which is derived from Cioffi et al. (1988). A single power law initial mass function, by mass, of slope $x = 1.35$, and lower and upper mass limits of $0.2 M_{\odot}$ and $65.0 M_{\odot}$, respectively, was used. ν is the astration parameter for the star formation rate in equation 4. The galactic wind time t_{GW} is in units of Gyrs. A binary parameter $A = 0.03$ was adopted. Initial dark-to-luminous mass and radial extents of ten were chosen. All post- t_{GW} ejecta was retained.

$M_{\text{g}}(0)$	ν	t_{GW}	m_{g}^{ej}	m_{O}^{ej}	$m_{\text{Fe}}^{\text{ej}}$	M_{V}	B-V	V-K	$[< Z >]_{\text{V}}$	R_{Ia}
1.0e6	188.9	0.006	3.5e5	2.2e2	1.0e1	-8.21	0.68	2.08	-2.28	0.03
5.0e7	209.7	0.007	1.2e7	3.2e4	1.5e3	-12.61	0.69	2.12	-1.56	0.03
1.0e9	123.1	0.016	1.7e8	3.0e6	2.0e5	-15.89	0.74	2.44	-0.51	0.04
5.0e10	46.0	0.077	3.4e9	1.1e8	9.3e6	-20.15	0.85	3.04	+0.13	0.04
1.0e12	17.3	0.440	1.7e10	4.9e8	7.5e7	-23.45	0.92	3.33	+0.44	0.05

more iron being ejected ($\sim 8\%$ more), due to the increased importance of Type Ia SNe at $t \gtrsim 0.3$ Gyr. The stellar lifetimes of Type II SNe progenitors for the $Z=0.001$ SSMM92 models are slightly longer than those for solar metallicity, by typically $\sim 10\%$. The main reason for this is that the lower metallicity models burn at a reduced luminosity, thereby lengthening their main sequence lifetimes.

One might be tempted to infer that the galactic wind epoch should be earlier for the higher metallicity τ assumption because of the shorter stellar lifetimes, and therefore, earlier SN explosion. As can be seen in Table 2, this is indeed the case.

Not surprisingly, the extremely different form for the TA71 stellar lifetimes, already encountered in Figure 1, leads to more substantial differences in the output models. The second-to-last entry in Table 2 shows that for $\nu = 17.3 \text{ Gyr}^{-1}$, the TA71 τ -formalism leads to earlier galactic wind times ($\sim 25\%$ earlier) than that found with the SSMM92 one, regardless of metallicity. In fact, the wind occurs early enough for the chosen model parameters, that the metallicity evolution does not continue to a late-enough epoch to ensure that the final stellar population’s colours are consistent with those seen today – e.g. the final V-K is ~ 0.25 mag too blue.

We might naively have expected the opposite behaviour, as the TA71 lifetimes range anywhere from 0 to ~ 6 times longer than those found by SSMM92, and thus the typical Type II SN explosion would occur later, leading one to perhaps expect a later wind. This is not what is encountered, the primary reason being that the substantially longer lifetimes encountered using TA71 means that the bulk of the Type II SNe explosions are delayed by many tens of millions of years in comparison with the SSMM92 lifetimes. This delay means that the bulk of the “TA71” explosions occur in a gaseous medium whose density has been depleted by the ongoing star formation during the “delay”. A reduced density leads to a greater SNR cooling time, and thus a greater thermal energy contribution per SN event, which in turn leads to an earlier wind time.

The final entry in Table 2 shows the implications of forcing the $M_{\text{g}}(0) = 10^{12} M_{\odot}$ model to coincide with that seen locally in giant ellipticals. This was done by fixing all the parameters, save the star formation efficiency ν , which was reduced from 17.3 Gyr^{-1} to 7.7 Gyr^{-1} . This leads to a wind epoch which is three to four times later, but it does mean that the mean photo-chemical properties of the stel-

lar populations have enough time to evolve to that seen locally. Because the ejection phase occurs so late, it should not be surprising to note that even with the reduced star formation efficiency, the total gas mass ejected is down $\sim 35\%$, and the ejecta’s $[\text{O}/\text{Fe}]$ is also reduced by ~ 0.15 dex (again, due to the increased contribution from the iron-important, longer-lived, Type Ia SNe), in comparison with the SSMM92 model.

The choice of stellar lifetime does not influence the resultant photo-chemical predictions by more than a few percent (provided the discrepant singular power-law form is avoided). Future versions of **MEGAW** will incorporate a fully self-consistent metallicity-dependent lifetimes, a la Bazan & Mathews (1990), but for the problems at hand, this does not appear to be a pressing need.

3.2.2 Stellar nucleosynthesis yields

Let us now turn our attention to one of the primary input ingredients – the Type II SNe nucleosynthesis yields. The basic data were introduced in Section 2.4, to which the reader is referred for specifics. Table 3 shows how the galactic wind epoch changes as a function of yield selection for the five sources. We only show the results for one initial mass – $M_{\text{g}}(0) = 10^{12} M_{\odot}$.

The star formation efficiency parameter $\nu = 17.3 \text{ Gyr}^{-1}$ for all entries in the table without an asterisk in the first column. Recall that this was the value required to ensure that the $10^{12} M_{\odot}$ model, in conjunction with the WW95 yields and the other parameters in the template models (Section 3.1), ended up with $V-K \approx 3.35$ and $[< Z >]_{\text{V}} \approx +0.4$ by the present-day. This is reflected by the first entry to Table 3.

One thing we note immediately from Table 3 is that for a given $\nu = 17.3 \text{ Gyr}^{-1}$, t_{GW} is not particularly sensitive to yield compilation, except that using LH95 leads to wind times which are $\sim 10\%$ earlier than the other four. This can be understood by recognising that over a wide range of Type II SNe progenitor masses, the LH95 yields are typically $\sim 30 \rightarrow 40\%$ lower than the others. This is due to the combination of their inclusion of stellar winds, and their semi-convection treatment (Ledoux criterion and minimal overshooting – Gibson 1997, in preparation).

The top panel of Figure 5 illustrates how the reduced Z yield favoured by LH95 manifests itself in the ISM evolution – Z_{g} is consistently $\sim 30 \rightarrow 40\%$ lower. The cooling time of a SNR shell increases as a function of decreasing metallicity

Table 2. Influence of stellar lifetime selection upon the galactic wind time t_{GW} (and hence, gas, O, and Fe, ejection, as well as resultant photometric properties). τ denotes the lifetime formalism adopted (all other ingredients as in Section 3.1. TA71= Talbot & Arnett 1971; GM82=Güsten & Mezger 1982; SSMM92=Schaller et al. 1992 – subscripts ‘1’ and ‘2’ refer to $Z=0.001$ and $Z=0.020$ lifetimes, respectively. Superscript * implies that ν has been adjusted from that shown in Table 1 in order to recover the same present-day photo-chemical properties shown in the earlier template table.

$M_{\text{g}}(0)$	τ	t_{GW}	m_{g}^{ej}	m_{O}^{ej}	$m_{\text{Fe}}^{\text{ej}}$	M_{V}	B-V	V-K	$[< Z >]_{\text{V}}$
1.0e6	SSMM92 ₂	0.006	3.5e5	2.2e2	1.0e1	-8.21	0.68	2.08	-2.28
1.0e6	SSMM92 ₁	0.006	3.2e5	1.5e2	5.1e0	-8.25	0.68	2.08	-2.49
1.0e6*	SSMM92 ₁	0.006	3.4e5	2.3e2	1.0e1	-8.22	0.68	2.08	-2.27
1.0e12	SSMM92 ₂	0.440	1.7e10	4.9e8	7.5e7	-23.45	0.92	3.33	+0.44
1.0e12	SSMM92 ₁	0.462	1.7e10	4.9e8	8.1e7	-23.47	0.92	3.33	+0.44
1.0e12	GM82	0.454	1.7e10	5.0e8	8.2e7	-23.47	0.93	3.35	+0.44
1.0e12	TA71	0.345	2.1e10	6.5e8	7.1e7	-23.44	0.86	3.11	+0.35
1.0e12*	TA71	1.476	1.1e10	2.5e8	4.6e7	-23.47	0.92	3.34	+0.48

Table 3. Influence of stellar nucleosynthesis yields selection upon the galactic wind time t_{GW} (and hence, gas, O, and Fe, ejection, as well as resultant photometric properties). m_{Z}^{ej} denotes the Type II SNe yields source (all other ingredients as in Section 3.1. A91=Arnett 1991; LH95=Langer & Henkel 1995; WW95=Woosley & Weaver 1995; TNH95=Thielemann et al. 1996; M92=Maeder 1992. Superscript * implies that ν has been adjusted from that shown in Table 1 in order to recover the same present-day photo-chemical properties shown in the earlier template table.

$M_{\text{g}}(0)$	m_{Z}^{ej}	t_{GW}	m_{g}^{ej}	m_{O}^{ej}	$m_{\text{Fe}}^{\text{ej}}$	M_{V}	B-V	V-K	$[< Z >]_{\text{V}}$
1.0e12	WW95	0.440	1.7e10	4.9e8	7.5e7	-23.45	0.92	3.33	+0.44
1.0e12	TNH95	0.463	1.6e10	5.5e8	7.4e7	-23.38	0.94	3.48	+0.49
1.0e12*	TNH95	0.161	2.5e10	9.7e8	8.9e7	-23.36	0.91	3.35	+0.42
1.0e12	A91	0.460	1.6e10	4.6e8	7.3e7	-23.39	0.94	3.47	+0.48
1.0e12*	A91	0.160	2.5e10	8.0e8	8.2e7	-23.36	0.91	3.35	+0.40
1.0e12	LH95	0.406	2.0e10	2.3e8	n/a	-23.45	0.93	3.29	+0.28
1.0e12*	LH95	0.736	1.5e10	1.9e8	n/a	-23.48	0.94	3.33	+0.30
1.0e12	M92	0.454	1.6e10	2.8e8	n/a	-23.40	0.96	3.45	+0.43
1.0e12*	M92	0.159	2.6e10	4.4e8	n/a	-23.37	0.92	3.33	+0.39

(Cioffi et al. 1988; Gibson 1995), and thus the lower ISM Z_{g} encountered with LH95 means that radiative cooling of each SN event is delayed relative to the other yield compilations. This greater energy per SN is what is responsible for the slightly earlier t_{GW} . We note in passing that the earlier t_{GW} means that the mass of gas ejected in the galactic wind is $\sim 20\%$ greater for a given ν .

Not surprisingly, the LH95 $\nu = 17.3 \text{ Gyr}^{-1}$ oxygen ejected at t_{GW} is $\sim 55\%$ lower than that found using the WW95, TNH95, or A91 yields. A similar lower oxygen ejecta mass is found with the M92 yields. Both LH95 and M92 have reduced oxygen yields due to stellar winds, and this is reflected in the oxygen ejected at t_{GW} in Table 3. Note though that while both LH95 and M92 models have lower oxygen ejected at t_{GW} , only LH95’s has a similarly reduced “Z” yield. M92’s Z yield is boosted by a greatly enhanced carbon contribution, especially for solar metallicity and masses $m \gtrsim 25 M_{\odot}$.

Again, just restricting ourselves to the $\nu = 17.3 \text{ Gyr}^{-1}$ numbers for the time being, we see that the TNH95 oxygen ejecta appears to be $\sim 10\%$ greater than the other models run without stellar winds (i.e. A91 and WW95). This may or may not be so – an uncertainty is introduced when using the TNH95 yields because the most massive model in their compilation is only $25 M_{\odot}$. We have just extrapolated beyond this last point in order to estimate the most massive Type II SNe yields (Section 2.4), which may not be optimal.

Note that the TNH95 oxygen yields closely parallel WW95 up to $m = 25 M_{\odot}$; anything beyond that is at best a rough estimate. This problem will be ever-present with the TNH95 yields due to its limited mass coverage.

The bottom panel for Figure 5 shows that the ISM $[\text{O}/\text{Fe}]$ converges toward $\sim +0.0 \rightarrow +0.1$ beyond $t \approx 0.3 \text{ Gyr}$, regardless of yield compilation. The TNH95 curve is ~ 0.1 dex greater than the A91 and WW95 at t_{GW} , and considerably higher for $t \lesssim 0.03 \text{ Gyr}$. Again, this is due primarily to the uncertain extrapolation to $m > 25 M_{\odot}$ – the TNH95 iron yield extrapolates to very small values, but more importantly, the oxygen yield grows very large beyond $m \approx 35 M_{\odot}$. This latter extrapolation tends to drive C/O in the earliest phases of the evolution to very low values (see the middle panel of Figure 5).

This middle panel of Figure 5 is a nice illustration of how the uncertainties in the stellar evolution can manifest itself. Whereas we saw that $[\text{O}/\text{Fe}]$ only spans $\sim +0.1 \rightarrow +0.3$ dex for the three yield compilations with iron for $t \gtrsim 0.1 \text{ Gyr}$, the C/O evolution is far more sensitive to the exact compilation used. C/O is seen to span almost a full dex during the same time period. Unlike the others, the WW95 curve has an initial decline in the C/O evolution due to the high mass $Z=0.0000$ stars which have very high C/O. The upturn in C/O beyond $t \approx 0.1 \text{ Gyr}$ is due primarily to the increased importance of intermediate mass stars undergoing multiple dredge-ups with stellar winds and PNe ejection.

Figure 5. Evolution of the ISM metallicity Z_g , and C/O and O/Fe ratios as a function of time for $\nu = 17.3 \text{ Gyr}^{-1}$. This ν value ensures the “Woosley & Weaver (1995)” model’s present-day photo-chemical properties are consistent with those observed locally. Evolution ceases at t_{GW} .

The enormous metallicity-sensitivity in the high mass carbon yields of M92 leads to the steeper slope for times $t \lesssim 0.1 \text{ Gyr}$, when compared with the other four yield sources.

Only the LH95 yields required a lower value for ν , albeit the adjustment was minor, the colours being reddened by only a few hundredths of a magnitude in V-K. The other three (besides the template WW95) required a factor of ~ 2 increase in the star formation efficiency, the result of which was a galactic wind occurring $\sim 0.3 \text{ Gyr}$ earlier. This had the desired effect of “bluing” the predicted V-K by $\sim 0.15 \text{ mag}$, in better agreement with the mean of the observations shown in Figure 7.

3.2.3 Thermal and binding energy evolution of the ISM

There are a number of inter-related aspects to the ISM energetics (thermal+gravitational binding) which have already been touched upon in Section 2.5. We will now look at a few examples which illustrate the sensitivity of t_{GW} to the assumed dark matter distribution (diffuse halo (DH) or dynamically dominant (DM)), as well as a couple of “hidden” uncertainties that plague many galactic wind models, but which are not widely appreciated. Arguments pertaining to the influence of assumed individual SNR energetics are delayed until Section 3.2.4.

Table 4 shows how t_{GW} , and the relevant present-day photo-chemical properties, vary with assumed initial dark-to-luminous mass and radial extent ratios. Recall that $M_D/M_L \equiv R_D/R_L \equiv 10$ for our template models. It is read-

ily apparent that the results are not sensitive to the dark matter content, provided it is distributed diffusely, following the prescription of Bertin et al. (1992). This is not surprising given the numerical example of Section 2.5, which showed the dominance of the luminous-luminous interaction term, as well as the results of Matteucci (1992). Obviously, for models in which the dark matter is more centrally condensed (e.g. $D=10$; $R=3$), the potential is deeper (equation 11), and it consequently takes longer for the ISM thermal energy to build up to the necessary level to overcome the binding energy, but the difference is not extreme, and could be minimised with a marginal increase in ν .

The situation is not particularly different if one makes the assumption that the dark matter is distributed similarly to the luminous matter, our so-called dynamically dominant (DD) model. In this case the gaseous binding energy follows equation 10 (after Saito 1979b). Table 5 shows how the model predictions for the template $10^{12} M_\odot$ model vary for initial dark-to-luminous mass ratios $D=0, 3$, and 10 for the DD model.

It can be seen that t_{GW} is not unduly influenced by the presence of a DD dark matter component. This is at odds with the conclusion of Matteucci (1992) who found very late wind epochs ($t_{\text{GW}} \gtrsim 9 \text{ Gyr}$) for $M_g(0) = 10^{12} M_\odot$, with $D=10$ (her Model C2). The source of the confusion can be traced to equation 10 – when the dark matter was distributed similarly to the luminous matter, Matteucci had $M_g(0)$ incorrectly in place of M_G in the denominator *outside* the brackets. The proper form is as shown in equation 10 (and was also laid down in its proper form by Ferrini & Poggianti 1993, following their equation 1). By using the luminous mass, as opposed to the gravitational mass, this leads to an order of magnitude overestimation of the gaseous binding energy (through equation 10).

In fact, as inspection of column 3 of Table 5 shows, t_{GW} actually decreases marginally as one goes to higher dark matter contents, simply because the corresponding increase in SNe energy efficiency \lll outweighs the accompanying increase in the gaseous binding energy (through equation 10). This behaviour, while perhaps interesting on a “mathematical” level, may or may not be wholly relevant on a “physical” level. Specifically, at some point, the validity of continually increasing R_G with M_G , for a given M_L , must be called into question, as the predicted surface brightnesses will be at odds with the observations. On top of this, as stressed by Bertin et al. (1994), and references therein, the dynamics of elliptical galaxies are better explained by assuming the presence of a massive dark halo. For all of these reasons, we will henceforth be restricting ourselves to the “dark halo” formalism of Bertin et al. (1992), in order to model the evolution of the gaseous binding energy.

\lll The increase in SN energy deposition efficiency with increasing total mass, simply comes about because in order to honour equation 16, as M_G increases, for a given M_L , there must also be a corresponding increase in R_G . By spreading the same M_L over a larger volume of radius R_G , the resulting decrease in the hydrogen number density means a corresponding increase in both the SN shell cooling time and the ISM merging time, through equations 9 and 14, respectively, of Gibson (1994b), and thus an increase in $\varepsilon_{\text{thSN}}$, through equation 12 of Gibson 1994b.

Table 4. Influence of diffuse dark matter halo distribution upon the galactic wind time t_{GW} (and hence, gas, O, and Fe, ejection, as well as resultant photometric properties), for the $M_{\text{g}}(0) = 10^{12} M_{\odot}$ model. $D \equiv M_{\text{D}}/M_{\text{L}}$; $R \equiv R_{\text{D}}/R_{\text{L}}$. All other ingredients as described in Section 3.1.

D	R	ν	t_{GW}	m_{g}^{ej}	m_{O}^{ej}	$m_{\text{Fe}}^{\text{ej}}$	M_{V}	B-V	V-K	$[< Z >]_{\text{V}}$	$< [\text{Mg/Fe}] >_{\text{V}}$
10	10	17.3	0.440	1.7e10	4.9e8	7.5e7	-23.45	0.92	3.33	+0.44	+0.13
10	3	17.3	0.719	8.5e9	2.1e8	4.4e7	-23.49	0.93	3.37	+0.49	+0.08
3	10	17.3	0.382	2.2e10	6.6e8	9.2e7	-23.44	0.92	3.32	+0.41	+0.13
0	n/a	17.3	0.357	2.5e10	7.7e8	1.0e8	-23.43	0.92	3.31	+0.39	+0.13

Table 5. Influence of dark matter, distributed similarly to the luminous component, upon the galactic wind time t_{GW} (and hence, gas, O, and Fe, ejection, as well as resultant photometric properties), for the $M_{\text{g}}(0) = 10^{12} M_{\odot}$ model. $D \equiv M_{\text{D}}/M_{\text{L}}$. All other ingredients as described in Section 3.1.

D	ν	t_{GW}	m_{g}^{ej}	m_{O}^{ej}	$m_{\text{Fe}}^{\text{ej}}$	M_{V}	B-V	V-K	$[< Z >]_{\text{V}}$	$< [\text{Mg/Fe}] >_{\text{V}}$
0	17.3	0.569	1.2e10	3.0e8	5.6e7	-23.47	0.93	3.35	+0.47	+0.11
3	17.3	0.453	1.6e10	4.6e8	7.2e7	-23.45	0.92	3.34	+0.44	+0.13
10	17.3	0.421	1.9e10	5.3e8	8.0e7	-23.45	0.92	3.33	+0.43	+0.13

One last “hidden” factor which can alter the calculated value of t_{GW} , is the formulation used for estimating the hydrogen number density n_0 – a prime ingredient in estimating the amount of energy per SN event which is made available to the ISM for driving a galactic wind, via its role in setting the cooling time for an individual SNR, n_0 should be based upon the ISM density at the time of the SN explosion (i.e. n_0 an explicit function of time). In order to simplify the energy calculations some early models (e.g. Arimoto & Yoshii 1987; Matteucci & Tornambè 1987) used $n_0(t) \equiv n_0(0)$, for all time $t \geq 0$. This point was first alluded to by Angeletti & Giannone (1990), and more recently by Gibson (1996b). The latter reference quantifies its effect as pertaining to Arimoto & Yoshii’s (1987) models, and the reader is directed there for more details.

3.2.4 Supernova remnant interior thermal energy evolution

One of the more interesting aspects of our work to date has been the re-examination of the role played by supernova remnant (SNR) thermal energy in powering galactic winds. As already alluded to in Section 2.6, the older galactic wind models (e.g. Arimoto & Yoshii 1987; Matteucci & Tornambè 1987; Bressan et al. 1994) adopt the classic Cox (1972) and Chevalier (1974) formalism for the energetics (our so-called “A” models). This form has since been supplanted by the more sophisticated models of Cioffi et al. (1988) (what we term the “B” models), and our work is the first to incorporate these improvements. Not only is the evolution of the individual SNR affected by this new formalism, the influence of overlapping shells has at least been treated to first-order. This turns out to be a crucial point, which was recognised in Larson’s (1974b) seminal paper, but again, not fully appreciated in many of the subsequent detailed models, save those of Dekel & Silk (1986), Babul & Rees (1992), and Nath & Chiba (1995). Gibson (1994b, 1995) has already examined some of the implications of the new formulations, and as such, only a few important new points will be made here.

The adopted energetics form can play a vital role in setting the galactic wind time (and consequently the end

of star formation, and the resultant photo-chemical properties). Table 6 illustrates how sensitive t_{GW} is to the SNR thermal energy evolution model. For brevity, we restrict ourselves to an analysis of the $M_{\text{g}}(0) = 10^{12} M_{\odot}$ model.

Recalling that Model B₂ has been adopted for the template models (Section 3.1), we see that its entry in Table 6 yields $t_{\text{GW}} = 0.44$ Gyr, with the appropriate present-day photo-chemical properties. Model A₀ is virtually indistinguishable from B₂ for this example, which is not surprising when a graphical comparison of the different $\varepsilon_{\text{thSN}}$ models is examined (see Figure 1 of Gibson 1994b). Model B₀ (Cioffi et al.’s 1988 direct analog to the classic Model A₀, but including radiative cooling of the interior and metallicity effects) leads to very late galactic wind times ($t_{\text{GW}} \approx 7 \rightarrow 8$ Gyr, for giant ellipticals), which for the model presented here would imply star formation rates of $\psi \approx 15 M_{\odot}/\text{yr}$ at redshifts $z \sim 0.4$, apparently at odds with the observations (Sandage 1986).

Models A₁ and B₁ lead to significantly earlier wind times as the late-time evolution of each individual remnant differs from the continual energy-loss models A₀ and B₂. For the same ν , this of course results in colours/metallicities which are too blue/low in comparison with the template Model B₂. Model B₁^{*} illustrates the results when ν is reduced to 2.9 Gyr^{-1} , in order to recover the proper photo-chemical properties. The later t_{GW} helps these properties, but at the expense, somewhat, of the predicted stellar $[\text{Mg/Fe}]$. More importantly, the reduced ν leads to an order of magnitude more gas being ejected at t_{GW} , despite its later occurrence.

Model B₃ is perhaps the best representation of an *individual* SNR’s evolution (Gibson 1994b), and the predicted wind time and properties are intermediate to the extreme models A₁ and B₁, and the template B₂. Of course, SNRs do not evolve in isolation; they eventually come into contact with neighbouring shells, overlap, and subsequent SNe explosions can occur in the subsequent rarefied bubble (or superbubble – e.g. Tomisaka 1992). Model B₃^{*} takes into account, roughly, the shell overlap effects. Similarly, Model B₃^{*} uses a reduced $\nu = 7.7 \text{ Gyr}^{-1}$ to better reproduce the photo-chemical properties. This model, as well as the Models B₁^{*} and B₂^{*} illustrate that treatment of the individual SNR ener-

Table 6. Influence of SNR thermal energy scenario upon the galactic wind time t_{GW} (and hence, gas, O, and Fe, ejection, as well as resultant photometric properties), for the $M_{\text{g}}(0) = 10^{12} M_{\odot}$ model – “A” models are based upon Cox (1972) and Chevalier (1974); “B” models are based upon Cioffi et al. (1988). See text for details. All other ingredients as described in Section 3.1. Superscript * implies that ν has been adjusted from that shown in Table 1 in order to recover the same present-day photo-chemical properties shown in the earlier template table (specifically, (V-K) and $[< Z >]_{\text{V}}$).

Model	ν	t_{GW}	m_{g}^{ej}	m_{O}^{ej}	$m_{\text{Fe}}^{\text{ej}}$	M_{V}	B-V	V-K	$[< Z >]_{\text{V}}$	$< [\text{Mg}/\text{Fe}] >_{\text{V}}$
A ₀	17.3	0.453	1.6e10	4.6e8	7.2e7	-23.45	0.92	3.34	+0.44	+0.13
A ₁	17.3	0.115	2.0e11	4.2e9	3.4e8	-23.22	0.87	3.03	-0.09	+0.10
B ₀	17.3	7.355	6.5e8	1.5e7	3.5e6	-23.55	0.94	3.45	+0.45	-0.16
B ₁	17.3	0.151	1.3e11	3.4e9	2.8e8	-23.30	0.89	3.13	+0.05	+0.10
B ₁ [*]	2.9	0.922	1.6e11	3.9e9	4.1e8	-23.32	0.94	3.31	+0.12	+0.04
B ₂ [*]	17.3	0.440	1.7e10	4.9e8	7.5e7	-23.45	0.92	3.33	+0.44	+0.13
B ₃	17.3	0.270	4.5e10	1.4e9	1.5e8	-23.40	0.91	3.28	+0.30	+0.13
B ₃ '	17.3	0.206	7.7e10	2.3e9	2.1e8	-23.36	0.90	3.22	+0.19	+0.12
B ₃ ' [*]	7.7	0.539	6.4e10	1.9e9	2.1e8	-23.39	0.94	3.35	+0.27	+0.10

Table 7. The mass fraction f_m tied up in stars more massive than $12 M_{\odot}$ in the four primary IMFs under consideration in **MEGaW**. A mass range of 0.2 to 65.0 M_{\odot} was assumed. S55=Salpeter (1955); AY87=Arimoto & Yoshii (1987); KTG93=Kroupa, Tout & Gilmore (1993); S86=Scalo (1986).

IMF	$f_m(m \geq 12 M_{\odot})$
AY87	0.323
S55	0.123
KTG93	0.061
S86	0.035

getics is an integral component in predicting the mass of gas ejected at t_{GW} . Ellipticals with similar final photo-chemical properties can differ in this prediction by up to an order of magnitude.

3.2.5 Initial mass function

We can anticipate the influence of IMF selection by simply looking at the mass fraction tied up in Type II SNe progenitors (i.e. $m \gtrsim 12 M_{\odot}$), as, for example, these are the primary source of α -elements in chemical evolution models, as well as the major contributor to the ISM energetics. Table 7 lists the mass fraction of stars $m \geq 12 M_{\odot}$ for each of the four primary IMFs under consideration, assuming a total mass range of 0.2 \rightarrow 65.0 M_{\odot} . One can see that an order of magnitude exists between the extrema, with the flatter Arimoto & Yoshii (1987, hereafter AY87) IMF having ~ 3 , ~ 5 , and ~ 10 times the mass of Salpeter’s (1955, hereafter S55), Kroupa et al. ’s (1993, hereafter KTG93), and Scalo’s (1986, hereafter S86) IMFs, respectively, locked into Type II SNe progenitors of initial mass $m \geq 12 M_{\odot}$.

In Table 8 we start with the template $10^{12} M_{\odot}$ model (from Section 3.1), but vary in turn the IMF selection between the four listed in Table 7. Parallel sets of models were run for two different SNe thermal energy forms – Models A₀ and B₂ of Section 2.6. We note that the binary parameter A (column 11 and equation 1) is a function of the IMF chosen, ranging from ~ 0.01 for the flat AY87 IMF to ~ 0.15 for the steep S86 IMF. These values ensure that

the predicted present-day Type Ia SNe rate (column 12) is $R_{\text{Ia}} \approx 0.05 \pm 0.03 \text{ SNu}$ (Turatto et al. 1994).

A primary conclusion to be gleaned from inspection of Table 8 is that the galactic wind time t_{GW} (column 3) is not particularly sensitive to the IMF, *provided* the star formation efficiency ν is kept constant (i.e. $\nu = 17.3 \text{ Gyr}^{-1}$), with t_{GW} ranging from 0.35 \rightarrow 0.57 Gyr.

A secondary point of interest can be inferred from the S55 and AY87 entries to the Model B₂ section of Table 8. One might naively expect that the flatter IMF (AY87) would *always* lead to an earlier wind time because of its greater proportion of Type II SNe, whereas we found that t_{GW} occurred $\sim 25\%$ later for the flatter AY87 IMF. This somewhat surprising behaviour can be traced to the metallicity dependence of the SN shell cooling time and ISM merging time (Section 2.6) in Cioffi et al. ’s (1988) evolutionary formalism. Metallicity terms were not considered by Cox (1972) and Chevalier (1974), which is why this behaviour has not been encountered in previous models (nor in the Model A₀ S55 and AY87 entries to Table 8), which have *all* been based upon these earlier supernova models. A detailed analysis of this unexpected behaviour is forthcoming, although a preliminary accounting can be found in Gibson (1995).

While t_{GW} may not be overly IMF-sensitive, because of the different proportion of low mass stars in the IMFs (i.e. those which can effectively lock-up and remove gas from possible subsequent enrichment), columns 4 through 6 show graphically that the predicted ejecta’s mass and abundance can be. For example, the S86 and AY87 IMFs, using SNR Model A₀ and $\nu = 17.3 \text{ Gyr}^{-1}$, lead to almost identical t_{GW} , but the latter model predicts ~ 9 times the gas mass at t_{GW} , and ~ 70 and ~ 11 times the mass of oxygen and iron, respectively. This last point is an interesting one – recall that $[\text{O}/\text{Fe}]^{\text{ICM}}$ lies in the range $\sim +0.1 \rightarrow +0.7$ (Mushotzky 1994) – the models just mentioned lead to ejecta with $[\text{O}/\text{Fe}]$ of $\sim +0.05$ (the AY87 IMF) and ~ -0.74 (the S86 IMF). Obviously we must fold in a cluster luminosity function before claiming anything, but the fact that one of the IMFs leads to ejecta which is almost a full dex outside the observed ICM $[\text{O}/\text{Fe}]$ should be a clue to the anticipated difficulty in replicating the observations using the steeper IMFs, a point which we addressed in Gibson & Matteucci (1997).

This iron overabundance relative to α -elements in the

Table 8. Influence of IMF selection upon the galactic wind time t_{GW} (and hence, gas, O, and Fe, ejection, as well as resultant photometric properties) for two different SNR thermal energy formalisms (Section 2.5), for the $M_{\text{g}}(0) = 10^{12} M_{\odot}$ model. “IMF” refers to the mass function source: S55=Salpeter 1955; AY87=Arimoto & Yoshii 1987; KTG93=Kroupa et al. 1993; S86=Scalo 1986. A is the binary parameter (equation 1) necessary to recover present-day Type Ia SNe rate. All other ingredients as described in Section 3.1. Superscript * implies that ν has been adjusted from that shown in Table 1 in order to recover the appropriate present-day photo-chemical properties (specifically, (V-K) and $[< Z >]_{\text{V}}$).

IMF	ν	t_{GW}	m_{g}^{ej}	m_{O}^{ej}	$m_{\text{Fe}}^{\text{ej}}$	M _V	B-V	V-K	$[< Z >]_{\text{V}}$	A	R_{Ia}	$< [\text{Mg}/\text{Fe}] >_{\text{V}}$
<i>SNe Thermal Energy Model B₂</i>												
S55*	17.3	0.440	1.7e10	4.9e8	7.5e7	-23.45	0.92	3.33	+0.44	0.030	0.05	+0.13
AY87	17.3	0.563	3.5e10	2.3e9	3.4e8	-23.08	0.95	3.97	+0.77	0.012	0.05	+0.31
AY87*	88.3	0.049	9.6e10	6.6e9	6.2e8	-23.03	0.83	3.38	+0.44	0.012	0.03	+0.34
KTG93	17.3	0.450	1.2e10	1.7e8	4.9e7	-23.90	0.86	2.96	+0.20	0.060	0.06	-0.10
KTG93*	3.8	4.180	7.0e9	1.0e8	5.5e7	-23.90	0.90	3.17	+0.33	0.060	0.08	-0.38
S86	17.3	0.353	9.3e9	1.1e8	5.4e7	-23.98	0.82	2.67	-0.01	0.150	0.06	-0.21
<i>SNe Thermal Energy Model A₀</i>												
S55*	17.3	0.453	1.6e10	4.6e8	7.2e7	-23.45	0.92	3.34	+0.44	0.030	0.05	+0.13
AY87	17.3	0.445	5.1e10	3.4e9	4.7e8	-23.05	0.95	3.94	+0.73	0.012	0.05	+0.31
AY87*	65.2	0.048	1.6e11	9.8e9	8.0e8	-22.93	0.85	3.39	+0.32	0.012	0.04	+0.32
KTG93	17.3	0.579	9.1e9	1.1e8	4.3e7	-23.92	0.86	2.98	+0.25	0.060	0.06	-0.15
KTG93*	7.7	2.418	5.5e9	7.5e7	4.8e7	-23.95	0.89	3.13	+0.31	0.060	0.07	-0.37
S86	17.3	0.467	5.7e9	5.1e7	4.3e7	-23.99	0.82	2.69	+0.10	0.150	0.06	-0.31

ejecta of the S86 model is of course due to the decreased significance of the Type II SNe in the steeper IMFs. Type Ia SNe play a correspondingly bigger role as the increased binary parameter A would suggest. Not only does the wind ejecta suffer from this Fe enhancement, but the predicted luminosity-weighted $[\text{Mg}/\text{Fe}]$ of the stellar population has a similar problem. The observed ratio in giant ellipticals is $\sim +0.2 \rightarrow +0.3$ (Worthey et al. 1992), in line with the AY87 IMF predictions of Table 8. The S86 and KTG93 values are in the range $\sim -0.2 \rightarrow -0.4$, well outside the observations, another argument against steep IMFs in ellipticals.

Studying the $\nu = 17.3 \text{ Gyr}^{-1}$ entries in Table 8, we can see that CML predictions for the S55 IMF match the mean of the observations (as this is inherent in the template models of Section 3.1). The flatter IMF, because of its enhanced enrichment history, by the same t_{GW} , has redder and more metal-rich stellar populations, at the present time. Conversely, the steeper IMFs are significantly bluer and metal poor relative to the mean of the observations. For example, the KTG93 $\nu = 17.3 \text{ Gyr}^{-1}$ models are ~ 0.4 mag too blue (in V-K) and ~ 0.2 dex metal-deficient, whereas the AY87 models are ~ 0.6 mag too red and ~ 0.3 dex too rich.

To remedy this, we show a series of models with ν varied in order to best replicate the present-day photo-chemical properties of the ellipticals. These models are represented with a * in column 1 of Table 8. For the flatter AY87 IMF, this means increasing ν by a factor of four to five, leading to a much earlier wind ($t_{\text{GW}} \approx 0.05 \text{ Gyr}$ as opposed to $\sim 0.5 \text{ Gyr}$). With the earlier wind comes ~ 3 times the mass of gas ejected at t_{GW} , and a more extreme $[\text{O}/\text{Fe}] \approx +0.2 \rightarrow +0.3$.

An even more important result is found when we look at the attempt to match the KTG93 and S86 IMF models with the observations. Specifically, it was found to be impossible to redden (or conversely, enrich) these models to the observed mean of V-K=3.33 ($[< Z >]_{\text{V}} = +0.44$) (for the luminosities involved here). Even reducing ν by factors of four to five could only redden the colours by ~ 0.2

mag, which is still ~ 0.2 mag blueward of the mean. By this point the wind epoch has shifted to $t \gtrsim 4 \text{ Gyr}$, which for the assumed cosmology would imply active observable star formation ($\psi \gtrsim 150 M_{\odot}/\text{yr}$) at redshifts $z \lesssim 0.9$, contrary to observations (Sandage 1986). By this time the $[\text{Mg}/\text{Fe}]$ of the stellar population has been decreased from an already untenable ~ -0.1 , to ~ -0.4 , even further removed from the observed overabundance of magnesium relative to iron. We haven’t shown the S86 predictions as they are even worse than the KTG93 ones.

This is an important result, and one which cannot be remedied within the closed-box formalism for chemical evolution currently adopted in **MEGAW**. For these steep IMFs, the metallicity increases slowly because of the lack of high mass stars in the IMF (at least, “slower” than for the S55 and AY87 IMFs). Because of this lack of super metal rich stars (compared to that seen with the flatter IMFs), all the stars formed with $Z=0.0$ (i.e. all those formed prior to the first SNe explosions – $t \lesssim 0.03 \text{ Gyr}$) tend to “pull” the colours/metallicities too blue/low.*** This would seem to indicate that this is partly an artifact of the star formation formalism. An infall model in which the mass of the gaseous component increases with time according to some accretion timescale (as opposed to the closed-box model in which all the gas is present and available for star formation at $t = 0$) may be an appropriate mechanism to “save” the steeper IMFs (e.g. Tantalo et al. 1995), although the difficulty in

*** This is a parallel manifestation to that of the “G-dwarf problem” in the Milky Way, and one from which all closed-box models of elliptical galaxy evolution suffer (Worthey et al. 1996).

reconciling the $[\text{Mg}/\text{Fe}]$ may still be problematic.*** Infall models will be investigated in a future paper.

More complex scenarios involving bimodal epochs of star formation and IMFs are a separate issue, and considered in Elbaz et al. (1995) and Gibson (1996a).

3.2.6 Star formation rate

It is apparent from Figures 6 and 7 that there is considerable scatter about the mean of the observed CML relation. A good part of this scatter is intrinsic (i.e. beyond observational error – Faber 1977). One obvious source of scatter can most likely be traced to the inherently simplistic handling of star formation in **MEGaW**.

To illustrate the effect of varying the star formation efficiency, we ran models with efficiency parameters ν (equation 4) arbitrarily scaled up or down by a factor two, as compared with the template values for ν listed in Table 1. How this impacts upon the galactic wind time, the mass and abundance of the ejected ISM, and the resultant present-day photo-chemical properties of the remaining stellar population, can be seen in Table 9, and graphically in Figures 6 and 7.

For all the models, the increased efficiency parameter (i.e. 2ν models) leads to an increased SNe rate, which for the more massive models (i.e. $M_{\text{g}}(0) \gtrsim 10^9 M_{\odot}$) results in earlier galactic winds, with a correspondingly greater mass of gas and metals ejected (up to $\sim 50\%$ more). For the lower mass (i.e. dwarf) models, the wind still occurs earlier, but there is less mass ejected because there is a ~ 4 Myr delay before the most massive Type II SNe progenitors explode – the increased SFR during this “delay” phase means less gas is available for expulsion at t_{GW} . The opposite behaviour is seen for the decreased efficiency parameter (i.e. 0.5ν models).

Figures 6 and 7 show the scatter in the observational planes for the factor of two variations in ν . The majority of the observed data points fall within the 0.5ν and 2ν curves. Obviously there are many uncertainties, but we do agree with Arimoto & Yoshii (1987) that much of the scatter in the observed photo-chemical correlations may be attributable to intrinsic scatter in the star formation efficiency.

4 SUMMARY

We have described, in some detail, the first version of **MEGaW**, our coupled photometric, chemical, and ISM thermal evolution code, based upon the classic framework of Larson (1974b). We have attempted to step through, one by one, each of the primary ingredients, in order to demonstrate how the timeframe for bulk star formation cessation (i.e. t_{GW}), as well as the resultant predicted present-day photo-chemical properties, changes, when adjusting any one

*** On the other hand, independent supporting evidence against steeper-than-Salpeter (1955) IMFs has already been put forth by Matteucci & Gibson (1995), Zepf & Silk (1996) and Loewenstein & Mushotzky (1996), based upon the significant α -element overabundances, with respect to iron, in the hot X-ray emitting intracluster gas.

Figure 6. Solid curve represents the predicted $[\text{Z}]-M_{\text{V}}$ relation for the template models of Table 1. The effects of doubling or halving the star formation efficiency parameter ν , from the template values, are also shown. Observational data from Smith (1985) (open circles) and Terlevich et al. (1981) (filled circles).

of these input parameters amongst what appear to be several plausible *a priori* selections. The sensitivity of the results to any one parameter has been hidden in previous studies of this sort.

We do not claim to have performed the strictest of statistical studies; the analysis shown is meant to be illustrative, more than anything. What we can conclude at this point though is:

- The present star formation rate formalism ($\psi \propto M_{\text{g}}$) precludes the use of IMFs steeper-than-Salpeter (1955) (Section 3.2.5).
- Discriminating between early ($t_{\text{GW}} \lesssim 0.1$ Gyr) and late ($t_{\text{GW}} \approx 0.5$ Gyr) galactic winds via photo-chemical constraints alone is not possible. For a given assumption regarding the efficiency of SNR energy transfer to the ISM, we can usually recover the present-day observations by varying the star formation efficiency parameter appropriately (Section 3.2.4; Gibson & Matteucci 1997).
- For non-extreme distributions, the role played by dark matter in setting t_{GW} would appear to be less important than at first envisaged by Matteucci (1992) (Section 3.2.3).
- An inverse wind phenomenon has been observed whereby t_{GW} actually increases with increasingly flatter IMFs. This comes about because of the metallicity dependence in the SNR evolution models of Cioffi et al. (1988), which tends to reduce the effective energy transferred per SN event to the ISM (Section 3.2.5).

An improved second version of **MEGaW** is still under development. Many enhancements to the basic code are currently underway, including most importantly, a full hydro-

Table 9. Sensitivity of t_{GW} , and the resultant present-day photo-chemical properties of ellipticals, to the star formation efficiency parameter ν . The template model of Table 1 is given first. Arbitrary scaling of ν up and down by factors of two are listed subsequently. All other input ingredients as discussed in Section 3.1.

$M_{\text{g}}(0)$	ν	t_{GW}	m_{g}^{ej}	m_{O}^{ej}	$m_{\text{Fe}}^{\text{ej}}$	M _V	B-V	V-K	[< Z >] _V
<i>Template ν</i>									
1.0e6	188.9	0.006	3.5e5	2.2e2	1.0e1	-8.21	0.68	2.08	-2.28
5.0e7	209.7	0.007	1.2e7	3.2e4	1.5e3	-12.61	0.69	2.12	-1.56
1.0e9	123.1	0.016	1.7e8	3.0e6	2.0e5	-15.89	0.74	2.44	-0.51
5.0e10	46.0	0.077	3.4e9	1.1e8	9.3e6	-20.15	0.85	3.04	+0.13
1.0e12	17.3	0.440	1.7e10	4.9e8	7.5e7	-23.45	0.92	3.33	+0.44
<i>Template $\nu \times 2$</i>									
1.0e6	375.9	0.004	2.2e5	7.5e-2	1.0e-5	-8.38	0.68	2.07	-3.23
5.0e7	419.5	0.004	8.5e6	1.7e2	3.9e-4	-12.69	0.68	2.07	-3.22
1.0e9	246.3	0.008	1.7e8	8.4e5	4.7e4	-15.94	0.70	2.15	-1.25
5.0e10	92.1	0.030	5.1e9	1.5e8	1.5e7	-20.17	0.78	2.73	-0.11
1.0e12	34.5	0.164	2.7e10	8.4e8	9.9e7	-23.44	0.87	3.19	+0.34
<i>Template $\nu \times 1/2$</i>									
1.0e6	94.0	0.010	4.1e5	1.3e3	5.4e1	-8.47	0.71	2.17	-1.37
5.0e7	104.9	0.014	1.3e7	1.4e5	7.6e3	-12.54	0.74	2.34	-0.76
1.0e9	61.6	0.032	1.8e8	3.8e6	3.4e5	-15.82	0.80	2.73	-0.25
5.0e10	23.0	0.202	2.2e9	6.8e7	6.9e6	-20.99	0.90	3.23	+0.29
1.0e12	8.6	1.145	1.2e10	3.4e8	7.1e7	-23.48	0.96	3.43	+0.48

treatment (Ferrini & Poggianti 1993), the inclusion of a gas infall term (Tantalo et al. 1995), and replacing the photometric evolution module with a full spectral synthesis one. A number of other minor enhancements were laid out in Gibson (1995).

Subsequent papers in this series will examine the evolution of galaxy cluster ICM abundances, damped Lyman- α systems, and stellar yield compilation differences.

ACKNOWLEDGEMENTS

First, and foremost, I would like to thank Francesca Matteucci for her boundless patience and assistance. Thanks also to Stan Woosley, Norbert Langer, and Friedel Thielemann for providing nucleosynthesis data prior to publication. Frank Timmes’ help during the debugging process is gratefully acknowledged, as is that of Guy Worthey’s. The consideration shown by the Astrophysics Department at Oxford during my two-year “sabbatical” cannot be emphasised enough. NSERC, Paul Hickson, and the University of British Columbia, are acknowledged for their respective financial assistance.

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Figure 7. Solid curve represents the predicted (V-K)-M_V relation for the template models of Table 1. The effects of doubling or halving the star formation efficiency parameter ν , from the template values, are also shown. Observational data from Thuan (1985) (open boxes) and Bower et al. (1992) (circles).

dynamical treatment of the elliptical’s evolution (e.g. David et al. 1991; Ciotti et al. 1991). A 1D-hydro code, based upon Thomas (1988), with the addition of diffuse dark halos, is being meshed with our photo-chemical evolution code. Coupled with more sophisticated radial star formation history scenarios, we will be exploring the origin and evolution of photo-chemical gradients in ellipticals. Other enhancements for Version 2 of **MEGaW** include a simple multi-phase ISM

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